Closed-Loop Atmospheric Ascent and Orbital Transfer Guidance

Project Number: 96-04

Investigators: G.A. Dukeman/ED13
J. Hanson/ED13

Purpose

To develop and test efficient closed-loop ascent and abort guidance (from liftoff through main engine cutoff (MECO)). Develop efficient multiburn orbital transfer algorithms.

Background

The guidance for the atmospheric portion of ascent to orbit has always been open-loop. Premission computed values of pitch and yaw command versus some independent variable such as altitude or relative velocity magnitude are typically stored on board for use during the highly constrained early portion of ascent.

Future launch vehicles like the Reusable Launch Vehicle (RLV) must be flexible and as autonomous as possible. This implies the need for a closed-loop ascent guidance scheme capable of issuing commands from shortly after liftoff until insertion to orbit. The proposed guidance scheme must be as simple as possible but still general enough to handle highly nonlinear path constraints and possibly several types of orbital insertion constraints.

An alternative approach is to formulate the ascent trajectory optimization problem as an optimal control problem transforming it into a multipoint boundary value problem. The multipoint boundary value problem can be solved using a numerical collocation procedure that uses "intelligent" interpolating functions based on close-form approximations of the state/costate system. The collocation procedure could be devised to work in a multiple shooting mode to reduce the sensitivity of the problem to guesses in initial costate. The optimal control problem would be formulated using three-dimensional equations of motion to allow flexibility and generality.

A byproduct of the above algorithm development is the capability to efficiently and accurately optimize multiple burn orbital transfers such as LEO to GEO missions. This is because the equations of motion and necessary conditions of optimality are the same whether the vehicle is being steered into orbit or the vehicle is already in orbit and an orbit change is desired. Currently, state of the art methods require as much as a few days of CPU time on high-speed computers to compute a near-optimal many-burn transfer.

Approach

For the RLV, closed-form approximations will be developed that allow for rapid solution for the associated optimal control problem. These approximations will be utilized in a numerical collocation procedure or possibly a variation of parameters integration scheme. Necessary conditions from optimal control theory will be derived as required to handle path constraints during ascent. Logic and equations will be developed to allow multiple shooting for multiple burn orbital transfer optimization. Optimal trajectories will be generated and compared with existing results in the literature when possible.

For the X–33 vehicle, the ascent and entry portions of flight are coupled because entry occurs only a few seconds after MECO. Therefore, entry as well as ascent contracts must be taken into account in the ascent trajectory design. These entry constraints include maximum heat rate, maximum body point temperatures, maximum normal acceleration, and sufficient energy margin to reach the landing site in the presence of dispersions. In order to satisfy all these constraints, it may be necessary to take advantage of a nominal attitude profile in the form of a preloaded table. To adjust to dispersions, e.g., off-nominal thrust, which would tend to cause low-energy at MECO, the nominal attitude profile provides a convenient first guess at a new attitude profile that would increase the energy at MECO. A linearly varying perturbation from the nominal attitude profile is proposed as a means for adjusting to off-nominal dispersions, as well as engine out abort scenarios.

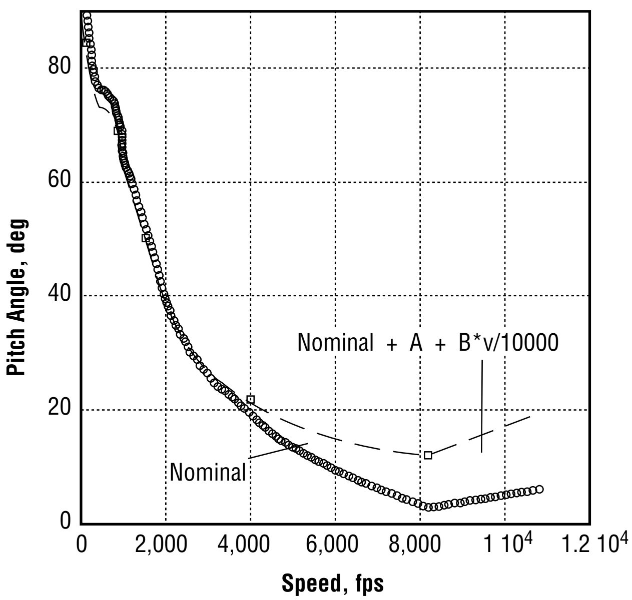

FIGURE 11.—Nominal and perturbed ascent pitch profile for X–33.

Accomplishments

Methods of real-time adjustment to X–33 dispersions/engine-out aborts were considered. The X–33 trajectories are highly constrained by ascent as well as entry phase constraints, e.g., ascent q-alpha, entry normal acceleration, entry body point temperatures, entry heating rate, sufficient MECO energy to get to the landing site, etc. It would be very difficult to generate ascent profiles that satisfy all these constraints using onboard software and computer resources. As an alternative, a precomputed nominal attitude profile is used in the form of a preloaded table, and then perturbations to this profile are computed in realtime to adjust to off-nominal conditions. The nominal profile serves as a first guess to a new profile that results in sufficient MECO energy. Because the new attitude profile is just a perturbation from the nominal attitude profile, the rest of the constraints, heating, etc., are close to their nominal values. Figure 11 illustrates a typical pitch angle profile, as well as the form of the perturbed pitch profile. It was found that the nominal attitude profile works quite well even for engine out aborts. For example, for a typical X–33 trajectory with MECO occurring at 205 seconds, if one of the two engines goes out after 40 seconds, the nominal attitude profile still results in acceptable MECO conditions that the entry guidance is able to adjust to, guiding the vehicle to the TAEM interface point.

State/costate vector propagation logic was developed to enable fast prediction of state/costate as a function of time. The aerodynamics, thrust, and gravity integrals are considered separately. The aerodynamics integral is evaluated by assuming the aerodynamics forces are piecewise constant over time intervals of length 500/qbar (psf). The gravity integral is evaluated assuming the gravitational acceleration is constant over time intervals of up to 100 seconds in length. The thrust integral is evaluated assuming piecewise constant mass rate and thrust magnitude and linearly time-varying thrust direction. This integral has an analytical solution in the form of a Taylor series in time which can be truncated at the cubic term to give sufficient accuracy over 200-second intervals. During the high dynamic pressure region of ascent, aerodynamic force variations limit the propagation step size whereas near the vacuum portion of flight, gravitational modeling accuracy, as well as phase transitions (g-limiting), limit the step size.

Planned Future Work

Numerical experiments will be conducted to determine tradeoffs in robustness and speed between various formulations such as collocation compared to the variation of parameters approach, and multiple shooting solution method compared to the straight shooting method. Much of the work will involve numerical algorithm and simplified model development. Because this research is behind schedule, the orbital transfer research will be pursued only as time allows.

Publications and Patent Applications

The final report for this project will be as a NASA technical memo.

Funding Summary ($k)

No funding was committed to this project.

Status of Investigation

This project was approved October 17, 1995. The research is currently behind schedule, but it is anticipated that the research will be completed by September 1998.